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Solar thermal application for the livestock industry in Taiwan

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A B S T R A C T

Solar water heating systems have proven reliable and economical. In Taiwan, the cumulative area of installed solar collectors at the end of 2014 was approximately 2.39 million m^2 and approximately 98% of those systems were installed in the domestic sector. Preheating water for livestock processing plants is cost-effective since heated water can be used for evisceration, sanitation during processing and for daily cleanup of plant. In this case study, detailed measurements are reported for parallel combined solar thermal and heat pump systems that are installed in a livestock processing plant. These results confirm that the hot water consumption, the mass flow rate and the operation of circulation and heat pumps affect the system's thermal efficiency. The combined operational effect is a factor in system design. The estimated payback period is less than the expected service period of the system, which validates the financial viability.

1. Introduction

Using renewable energy yields energy savings and environmental benefits. In Taiwan, imported fuel accounted for 97.58% of the energy supply in 2013 [1], so renewable energy has received increasing support, particularly with the passing of the Renewable Energy Development Bill in April 2010. Water heating constitutes a major form of energy consumption in the domestic and commercial sectors [2]. Taiwan has a subtropical climate (22–25° North), so the annual global solar radiation ranges from 1200 to 1700 kWh/m^2 [3]. The subsidy programs (1986–1991, 2000–present) introduced by the Bureau of Energy under the Ministry of Economic Affairs (BEMOEA) for solar water heaters (SWHs) mean that the cumulative area of solar collectors installed was approximately 2.39 million m^2 in Taiwan at the end of 2014 and approximately 0.3 million systems (or 1.6 million m^2) are currently operational [4]. Dissemination of SWHs in Taiwan was reviewed by Chang et al. [5,6] and Lin et al. [7]. More than 98% of SWHs have been installed in the domestic sector and the limited commercial application of industrial heat generation is attributable to the lack of experience in system design and uncertainty about the potential benefits to end users.

Industrial heat processes represent an area where solar heat applications can be used in various sectors [8] and the required temperatures range from 60 to 260 °C [9]. Lauterbach et al. [10] showed that the process temperature, the collectors and the load profile are the most important factors for system performance in a brewery. An increased in the return temperature from 20 °C to 40 °C results in a 35% reduction in system yield. A shorter operation with doubled mass flow also reduces the system yield. Plants in the livestock industry could make good use of solar heat for evisceration, sanitation during processing and daily plant cleaning. In Taiwan, pork is the most commonly consumed meat (comprising 40% of total

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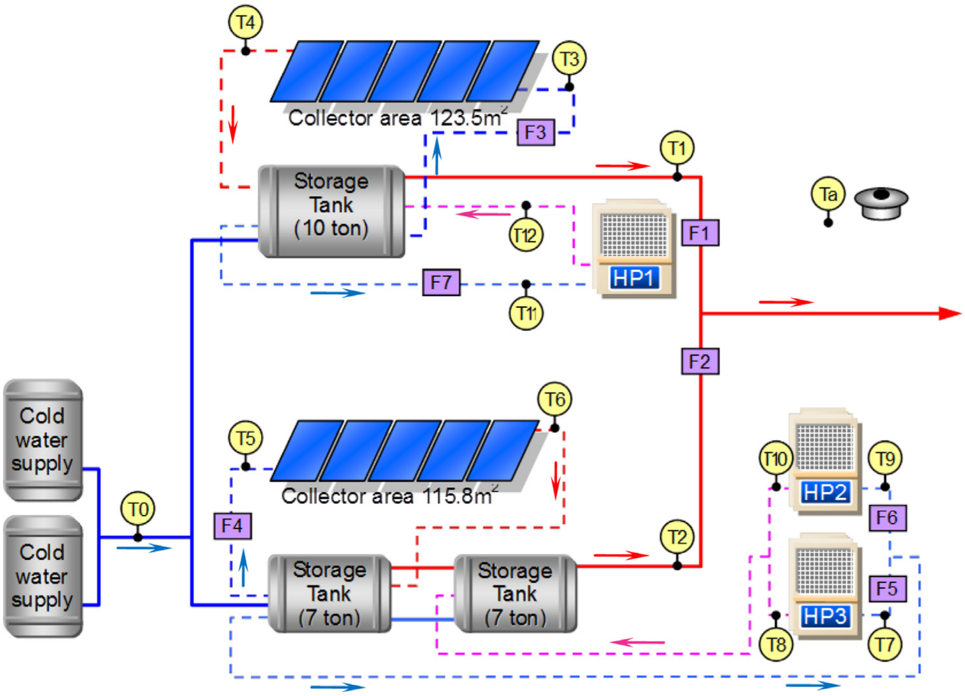

Fig. 1. A schematic drawing of the SWHs and the monitoring devices.

meat consumed). 8457 pig farms in Taiwan also supplied approximately 7.47 million pigs in 2013 [11]. To promote SWHs in the livestock industry, SWH system performance and financial viability must be determined. Furthermore, heat pumps (HPs) allow high thermal efficiency. In terms of the ambient air temperature, a suitable dead-band temperature is essential for air-to-water HPs. The potential benefits of combining SWHs and HPs for hot water production have also been studied [12]. However, the financial viability depends upon heating operation conditions. In this case study, HPs are used as a back-up heating source. Both SWHs and HPs supply heat to water storage tanks independently. Field measurements for the system in a slaughterhouse are conducted. The data is then used to estimate the real benefits for end users and provide justification for the use of solar thermal energy in the commercial sector.

2. Field measurement setup

Yunlin County (1270 pig farms) ranks first in terms of pig production (producing 24.36% of all pigs in Taiwan) [11]. Therefore, the Yunlin meat market (23°43′40″N, 120°25′43″E) in Southern Taiwan near the Tropic of Cancer (annual solar radiation = 6712 MJ/m^2) was chosen for the case study to evaluate the performance of a combination of solar thermal and HP system. Fig. 1 shows the two independent SWHs and HPs that were used for scalding and de-hairing. The effective area of the solar collectors A_{sc} (glazed flat-plate type) was 123.5 m^2 for System 1 (installed in March, 2012) and 115.8 m^2 for System 2 (installed in August, 2010). The south-facing solar collectors were installed on the roof at a tilt angle of 18.5°. One 10-ton and two 7-ton storage tanks were also installed. Temperature set control (= 5 °C) was used to control pump operation for the SWHs. The mass flow rate setup was 0.028 and 0.019 kg/m^2/s for Systems 1 and 2, respectively. As a back-up heating source, the HPs were switched on when the temperature in the storage tanks is less than 50 °C and their flow rate ranged from 105 to 118 L/min. A boiler that uses low sulfur light fuel oil was also available for the required temperature of 63 °C.

Several monitoring devices were installed to determine the system performance. A precision spectral pyranometer (PSP, Eppley Laboratory, Inc.) measured the incident horizontal solar radiation. Seven Macnaught flow meters (M2SSP-1R, denoted as F1–F7) were positioned along the cold water supply line to the hot water storage tank (hot water consumption) and along the circulation line from the bottom of the storage tank to the inlet of the collectors (circulation flow rate). Fourteen platinum resistance thermometers (denoted as T_a, T0–T12; 1/10 DIN Class B, Izuder Enterprise) were installed to monitor the ambient and local water temperatures. The energy consumption of the HPs (HP1: 38.4 kW; HP2 and HP3: 40.6 kW) was recorded using power meters. Data from the monitoring devices was sampled every 10-s using a National Instrument's data acquisition system (cFP-AI-110 and cFP-RTD-124).

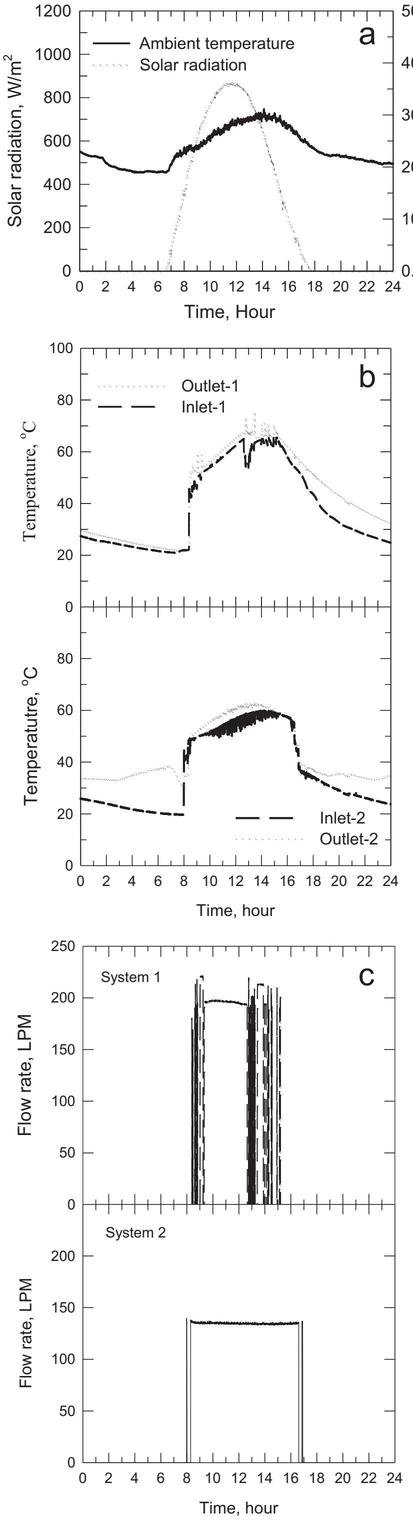

Fig. 2. (a) The daily variations in solar radiation and outdoor temperature, (b) the inlet and outlet temperatures of the collectors, and (c) the hot water consumption pattern for March 25, 2013.

3. The operating performance of the system

3.1. Solar water heaters and heat pumps

Solar collector or SWH certification is mandatory when filing for rebates in the current subsidy program. In a laboratory test, the Chinese National Standard (CNS 15165-1-K8031-1) for a flat-plate solar collector is in compliance with the existing international standards. The intercept of collector efficiency curve, $F_R(\tau\alpha)$, is larger than 0.75 while the slope of the curve, F_RU_L, is less than 7.0. The thermal efficiency η (≥ 0.5, Chinese National Standard (CNS) 12558-B7277) of a thermosyphon SWH is calculated using the following formula. The standard test conditions specify the daily horizontal solar radiation per square meter (≥ 7 MJ/m^2).

$$\eta = mC_p(T_f - T_i)/(A_{sc}G) \tag{1}$$

C_p is the specific heat; MJ/(kg °C), m is the water mass flow; kg, T_i is the initial temperature in the hot water storage tank; °C, T_f is the final temperature in the hot water storage tank; °C, A_{sc} is the effective area of solar collectors; m^2, and G is the daily horizontal solar radiation per square meter; MJ/m^2.

In this study, data from March 25, 2013 to June 30, 2013 was used to determine the system performance. For example, Fig. 2a shows the plots of solar radiation and ambient temperature data for the daily record on March 25, 2013 (a typical working day). The outdoor temperature ranges from 20 to 30 °C and the peak solar radiation was approximately 870 W/m^2. The daily solar radiation is approximately 5.77 kWh/m^2 and the solar energy generated by Systems 1 and 2 is 712.6 and 668.2 kWh, respectively. The inlet and outlet temperatures of the collectors are plotted in Fig. 2b. The peak inlet temperatures of collectors are 65.5 and 60.0 °C and the peak outlet temperatures are 75.9 and 62.9 °C for Systems 1 and 2, respectively. These maxima correspond to a rise in temperature of approximately 30–45.9 °C above the ambient air temperature. Hot water is consumed between 08:00 and 17:00 (Fig. 2c) and the daily hot water consumption (Systems 1 and 2) is 26,045 l. Between March 25 and June 30, the daily hot water consumption for System 1 is substantially lower than that for System 2, as shown in Fig. 3. The peak values for hot water consumption are 13,098 L/d and 26,573 L/d for Systems 1 and 2, respectively. As shown in Eq. (1), $\eta \propto (T_f - T_i)/(A_{sc}G)$, but the efficiency of a SWH in the field is different to that for a laboratory test. To estimate potential benefits of a SWH in a specific climate, the initial and final temperatures of the water storage tank are not known, but the weather agencies provide the historical data for G. An empirical correlation between η and G is

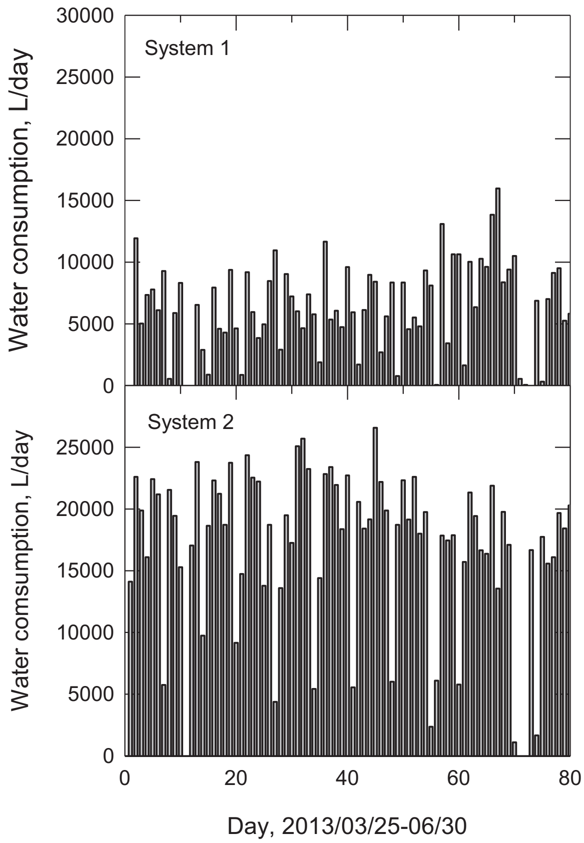

Fig. 3. The daily hot water consumption, March 25, 2013–June 30, 2013.

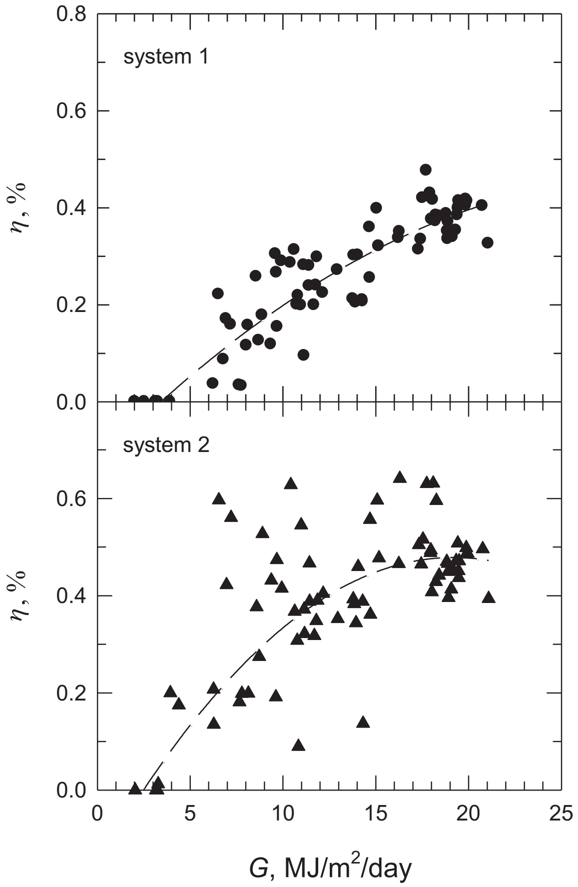

Fig. 4. The thermal efficiency of the SWHs.

presented in Fig. 4. For System 1, η increases as G increases (≥ 6 MJ/m^2). The peak value is 0.476. For System 2, η varies widely with G and peaks at 0.641. Hot water use is crucial to increase the thermal efficiency of SWHs. The efficiency in the field for System 2 is higher because more hot water is withdrawn from the system, as shown in Fig. 3.Li et al. [13] found that a combination of SWHs and HPs is effective for hot water production. The coefficient of performance (COP) of a HP is defined as the ratio of the total useful heat supplied to the total power consumption.

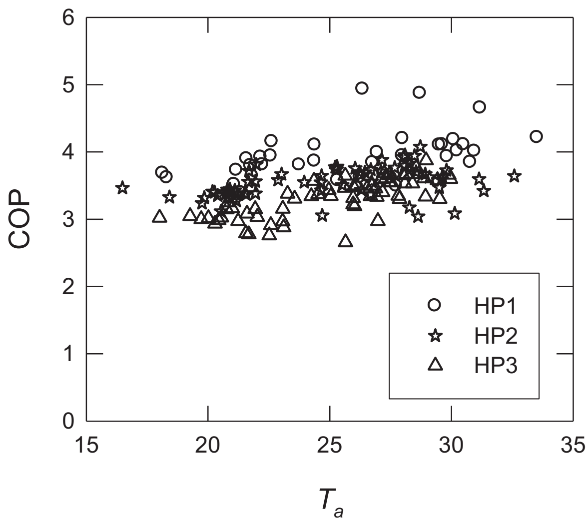

Fig. 5. The COP for heat pumps.

Table 1
Energy collection and consumption from March 25 to June 30.

kWh	System 1	System 2	Sum
Collected energy, SWHs	12,300	16,141	28,441
Collected energy, HPs	5075	41,859	46,934
Total collected energy	17,375	58,000	75,375
Energy consumption	17,375	39,542	56,917
Circulation pump	195	1129	1323
Heat pumps	1422	13,654	15,076

Table 2
The operational performance of the system.

Month	G, MJ/m^2	System 1		System 2		
		η	COP-HP1	η	COP-HP2	COP-HP3
April	10.72	0.170	3.76	0.260	3.50	3.13
May	13.81	0.272	4.22	0.419	3.51	3.35
June	14.18	0.277	4.09	0.351	3.66	3.53

$$COP = mC_p(T_{wf}\_T_{wi})/W_{comp} \tag{2}$$

T_{wf} is the final water temperature; T_{wi} is the initial water temperature and W_{comp} is the energy consumption of the HP.

A study by Huang and Lee [14] found that the COP for a solar-assisted heat pump water heater is proportional to T_w–$T_{a,ave}$, where T_w=($T_{wf}T_{wi}$)/2 and $T_{a,ave}$ is the average ambient temperature. In Fig. 5, the COP of HPs varies from 2.6 to 4.9, for T_a=18–33 °C. Since the value of T_w for System 1 is greater than that for System 2, the COP for HP1 is higher than those for HP2 or HP3.

3.2. Operational performance

The useful energy gains for the SWHs and HPs from April to June 2013 are summarized in Table 1. For the SWHs, the collected solar energy is 12,300 and 16,141 kWh for Systems 1 and 2, respectively. The collected energy for the HPs (COP=3.13–4.22) is 46,934 kWh. A comparison of the system's performance shows that HP1 was the least used and was typically deactivated during the measurement period. The ratio of collected solar energy to the total energy supplied by the combined system is 70.8% and 27.8% for Systems 1 and 2, respectively. Table 1 also shows that only 68% of the total collected energy for System 2 was consumed, which represents inefficient operation of the HPs. The electricity consumption for the circulation pump of System 2 (7% of the total energy collected) is also substantially higher than that of System 1 (1.6% of the total energy collected), so a suitable control strategy is required to ensure effective energy savings for the system. However, the net energy savings between March 25 and June 30, 2013 are 41,849 kWh.

The monthly operational performance for the system, from April to June 2013, is detailed in Table 2. The solar thermal efficiency (η=0.170–0.419) is substantially lower than the CNS standard for a thermosyphon SHW (i.e., $\eta \geq 0.5$), particularly in April. This is partially attributable to a decrease in monthly solar radiation. The peak daily hot water consumption of System 1 is also approximately half that for System 2 (Fig. 3), so a SWH that operates in conditions where there is greater hot water consumption is more efficient. Moreover, the mass flow rate is 0.028 and 0.019 kg/m^2/s for Systems 1 and 2, respectively. Furbo et al. [15] found that a low mass flow rate for a SWH results in greater thermal efficiency, so a reduction in the mass flow rate for System 1 could ensure greater efficiency. Notably, the monthly COP for HP1 (3.76–4.09) is slightly greater than that for HP2 (3.50–3.66) or HP3 (3.13–3.53).

In terms of system economics, a simplified break-even analysis is detailed. The maintenance cost and the annual change in price for the substituted fuel is not considered. The initial costs of the SWHs and the HPs is 2.15 and 1.15 million NT$ (1 US $ ≈ 31 NT$), respectively. SWH subsidies from the BEMOEA and Yunlin County was approximately 0.7 million NT$. The cost of low sulfur light fuel oil was 22,779 NT$/kL in 2014 and its heating value is 40.19 MJ/L [1]. Assuming a heating efficiency of 80%, the substituted fuel savings are estimated to be 0.4 million NT$/year. Therefore, the payback period is estimated to be 6.5 years, which is less than the expected service period for a SWH (15 years). This verifies the financial viability of a combined SWH and HP system for industrial water heating.

4. Conclusions

Solar water heating is the most successful example of the domestic use of renewable energy in Taiwan. This case study uses field measurements for a combination system that is installed in a slaughterhouse. The results demonstrate that the combined system is eminently suitable for industrial heat processes in the livestock industry. A simplified break-even analysis demonstrates the financial viability of the combined system. However, proper control settings for the operation of the circulation pumps and the HPs are essential if energy savings are to be maximized.

Acknowledgments

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